TECHNOLOGY REVIEW OF ACCELERATOR FACILITIES

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ABSTRACT

New initiatives in basic science, accelerator engineering and market development, continue to stimulate applications of electron accelerators. Contributions from scientific experts in each of these segments have been assimulated to reflect the present status of accelerator technology in radiation processing.

KEYWORDS

Electron Accelerators, irradiation facilities, radiation interactions, radiation applications, radiation sources.

INTRODUCTION

Application of accelerator technology to radiation processing is expanding in many diverse areas. This paper compiles data and status reports from experts in both accelerator design and radiation application. It is not intended to be comprehensive but rather indicative of the activity of new applied technologies using electrons with energy greater than 1.0 MeV.

The paper is divided into three main subject areas. First, recent important events and new initiatives in the field of radiation physics are selected. This is supplemented by a summary of some recent, large-scale industrial plans in the USSR for new applications of radiation science in solid state chemistry. Second, electron accelerator engineering is the base technology for expensive new synchrotron light facilities and the plans for many new facilities will be described. Also, new industrial accelerator designs and operations are reported from information provided by engineering and applied science groups in Eastern Europe. Finally, the market development of new radiation applications has been enhanced by new linear accelerator facilities which have recently been commissioned. These and other new linac developments will be mentioned and references given.

BASIC SCIENCE

Nuclear Application

Potentially the largest application of electron-based radiation technology in future decades could come from the incineration of nuclear waste. Over the past few years, the U.S. advanced reactor R&D effort has focused on the Integral Fast Reactor (IFR) technology (Wade and Chang, 1988) because it offers promise in addressing the three main requirements of breeding, safety and waste. The first two have been demonstrated and the waste management potential of the IFR concept is under intensive study. It is convenient to categorize the nuclear waste constituents into two parts: fission products comprised of hundreds of various isotopes and actinides comprised of uranium and the transuranic elements--neptunium, plutonium, americium, curium, etc. Fission products are produced by fissioning of uranium, plutonium and the other trace actinides, and transuranics are produced as a result of neutron capture.

The relative radiological risk factors for the fission products and actinides contained in the light water reactor once-through spent fuel cycle are plotted in Figure 1 as a function of time after discharge from the reactor. The radiological risk factor of the spent fuel is normalized to the cancer risk associated with the original natural core. Figure 1 illustrates the dominance of the long-term radiological risk of actinides over all other fission products. Separation of the actinides and the use of photofission to create stable and short-lived isotopes is now considered to be a possible option. As part of the OMEGA program (Atoms in Japan, 1988) Japanese scientists are planning to build a 100 MeV electron linac with an average power of 10 MW beginning in 1991 to help establish the possibility of

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eliminating long-term storage. The development of such high power electron accelerators is likely to have a profound impact on the more traditional methods of radiation processing.

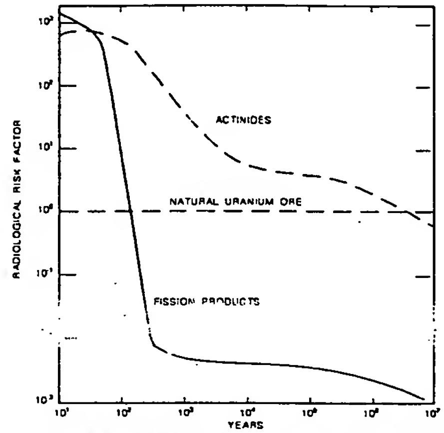

Fig. 1. Relative Radiological Risk Factor of Fission Products and Actinides in the LWR Spent Fuel, Normalized to Their Original Uranium Ore (Data Source: L. Koch, J. of the Less-Common Metals, 122, 371-382, 1986).

Activation Studies

In radiation processing, activation of the product by high energy electrons has sometimes been of concern. Lone et al. (1989), have just completed a theoretical study of the activation of processed meat using 10 MeV electrons and bremsstrahlung from 5 MeV electrons.

The results are shown in Table 1. They concluded that the radioactivity that could be produced by the known processes is less than 10 mBq/(kg.kGy) just after the irradiation. This result is consistent with experiments recently carried out by Miller and Jensen (1987).

ACTIVITY				RADIOACTIVITY IN IRRADIATED MEAT AT t = 0		
ELEMENT	Wt%	CAPTURE IN ELEMENT	NUCLIDE	CAPTURE IN ISOTOPE	5 MeV* X-RAYS Bq PER (kg. kGy)	10 MeV* ELECTRONS Bq PER (kg.kGy)
H	9	9.38 E-1	^{3}H	2.4 E-7	2.5 E-9	1.1 E-10
C	18	1.64 E-3	^{14}C	5.2 E-6	1.1 E-10	4.6 E-12
N	2	6.0 E-2	^{14}C	6.0 E-2	1.3 E-6	5.5 E-8
O	70	2.4 E-4	·			
Na	7.5 E-2	5.4 E-5	^{24}Na (15.2)h	5.4 E-5	3.9 E-3	1.7 E-4
Cl	5.6 E-4	2.0 E-2	^{36}Cl (3.0E5)y	2.0 E-2	8.3 E-9	3.5 E-10
Hg	5. E-6	3.4 E-6	^{199}Hg (42.6)m	1.7 E-11	2.4 E-3	1.0 E-10

* Assumes 90% neutron leakage; for no leakage multiply by 10.

TABLE 1: ELEMENTAL CONTRIBUTIONS TO NEUTRON CAPTURE IN MEAT

Solid-State Chemistry

The adiabatic hardening of steel using high power, low energy, electron accelerators is a new application reported by Bikovsky et al. (1988) in the USSR. The conditions necessary to achieve significant mass transfer, carbon diffusion and recrystallization are that the activation energy is high and that the thermal conductivity is low. Within times less than 20 ms the surface of the steel can be raised to almost melting point with electrons of 1.5 MeV penetrating 0.8 mm into the metal. Improvement to surface hardness of up to 50% and scratch resistance by a factor of 5 have been reported to a variety of steel alloys and other materials.

ACCELERATOR ENGINEERING

Synchrotron Light Sources

Accelerator designs for synchrotron light sources are likely to capture most of the capital investment for new technology in radiation processing over the next few years. The target of reaching a spacial resolution of 0.25 μm in the attempt to produce a 64 M bit computer chip using x-ray lithography has spawned over 40 facilities either under construction or planned during 1989. Table 2 provided by Hoffmann (1989) in a recent study lists the projects and their status. High power linac technology is needed for the injector to the storage ring and it is also needed to provide the make-up energy to the large circulating currents within the ring itself.

E (GeV)	Injector	Radiator	Status	Reference
(A) CW Sources				
1	1 GeV Linac	Storage Ring	Study	Brookhaven (1986)
1	10 MeV Linac +0.35 GeV	Synchrotron - Storage Ring	Study	Younger (1987)
1	0.1 GeV Microtron	Synchrotoron - Storage Ring	Study	Eriksson (1987)
1	1 GeV Linac*	Storage Ring*	Study	Shimano (1987)
1	25 MeV Linac	2.5 T Magnets in 1.5 T Synchrotron Storage Ring	Study	Maxwell (1988)
1.5	0.15 GeV Microtron	Synchrotron - Storage Ring	Study	Einfield (1988)
0.7	0.7 GeV	Racetrack Integral with Microtron	Study	Mileckowsky (1987)
0.6	0.6 GeV Linac	Circular Storage Ring	Concept	
0.65	0.15 GeV	Circular Synchrotron - Storage Ring	Const.	Takahashi (1987)
0.43	8 MeV Linac	Circular Synchrotron - Storage Ring	Study	Trinks (1982)
0.6	50 MeV Microtron	Racetrack Synchrotron - Storage Ring	Const.	Heuberger (1968)
0.6	200 MeV Linac	Racetrack Synchrotron - Storage Ring	Const.	Wilson (1988)
0.6	0.1 GeV Linac	5 T Synchrotron - Storage Ring	Concept	
0.6	0.1 GeV Microtron	7.5 T Undulator in 1.8 T Storage Ring	MAX upgrade	Eriksson (1988)
0.4	0.4 GeV Linac	Circular Storage Ring	Concept	
0.35	0.35 GeV Linac	15 T Bending Magnet Storage Ring	Concept	App. VI
0.35	0.1 GeV Linac	1.8 T Synchrotron Storage Ring with 15 T Radiator	Concept	
0.35	0.35 GeV Linac	Circular Storage Ring	Concept	App. III
(B) Pulsed Sources				
0.3	Gun	Circular Pulsed Synchrotron	Model	Anevsky (1987)
0.3	0.3 GeV Linac	20 T Pulsed Magnet Radiator	Concept	Felber (1987) App. VII
0.3	0.3 GeV Linac	20 T Superconducting Magnet Radiator	Concept	
0.3	0.3 GeV Linac	20 T Superconducting Beam Trap	Concept	Felber (1987)
0.1	0.1 GeV Linac	200 T Z-Pinch Radiator	Concept	Felber (1987) Lampel 1989)
0.03	0.03 GeV Linac	2000 T Z-Pinch Radiator	Concept	Felber (1985)
(c) Transition Radiation Source				
0.1	0.1 GeV Linac	Be Foil Stack	Concept	Moran (1986) App. V
(D) Plasma Sources				
	Laser	Plasma	Model	Pepin (1968)
	Focus	Plasma	Model	Eberle (1985)
	Gas Puff 2 - Pinch	Plasma	Model	Kitayama (1986)

* SUPERCONDUCTING

TABLE 2: LITHOGRAPHY X-RAY SOURCES

Market intelligence has suggested a market of 160 machines. The cost of each accelerator is estimated to be about 20M$ and it is only weakly dependent on whether room temperature or superconducting magnets are used. As an example of how the cost of electron accelerators compare with the cost of the processing facilities in which they fit, Godel (1986) has estimated the total cost of the X-ray lithography development facility at Brookhaven to be 395M$.

Industrial Developments

The transfer of accelerator technology to industry is well advanced in Eastern Europe and the USSR. At the Central Institute of Isotope and Radiation Research in Leipzig a low energy accelerator (200 keV) with a dose rate capability of 1.1 MGy/s, a linear accelerator (4-10 MeV) with nano-second pulse capability and a microtron (23 MeV) are being used to develop new radiation processes as well as produce radioisotopes and execute photon activation analyses (Leonhardt et al, 1988). All of the work is closely linked to industry.

The Warsaw Institute of Nuclear Chemistry and Technology with its established reputation in electron beam processing has commissioned two new facilities in 1988 (Zimek and Stachowicz, 1988). These are a self-excited linac (2 MeV, 20 kW) for processing shrink tubing and a new 2 MeV dc machine for applied research. Next year two 10 MeV linacs, designed and manufactured at Swierk will be commissioned in two pilot plants for food irradiation, while a year later a new 10 MeV linac is planned for pulse radiolysis. The Institute continues to run its 9 kW linac of 1971 vintage mainly for processing medical products and in 1987 this excellent Soviet machine operated for 4,200 hours sterilizing over 7 million medical pieces at a sterility level of better than 10^{-6} micro-organism per article. In Hungary, the Research Institute for Plastics (Czvikovszky, 1988) and the Institute of Isotopes have produced new building materials which have found their way to the consumer as well as pioneer pilot projects in food irradiation (Kovacs and Hargittai, 1988).

Electron accelerators for industrial use are highly developed in the USSR. This results from the approaches taken by the Efremov Institute in Leningrad and the Institute for Nuclear Physics at Novosibirsk. The latter Institute has provided over 30 machines to industry of which 10 are outside the USSR. The low energy designs are of the transformer-rectifier type (ELU series) while self-excited linacs (ILU series) are used for high energy applications. The high monochromaticity of the beam accelerated by the ELU series machines is such that a 50 mA dc beam punctures a hole not bigger than 3 mm wide in the exit window and permits a free exit to atmosphere by a system of differential pumping. This eliminates the window problem with high power beams and provides a power density of 10^6 W/cm^2 for the solid state applications mentioned above.

The self-excited linac continues its development as a prime industrial linac (Auslender et al., 1988). Figure 2 is a schematic of this widely used machine. The single cavity is powered by a robust low frequency triode. The cavity provides the tank circuit for the triode and beam loading of the cavity is automatically compensated. Back bombardment and multipactoring are suppressed by a dc voltage applied to a gap at the mid-plane of the

resonator. The accelerators are simple, small and reliable with some of them operating continuously up to 6,500 hours per year.

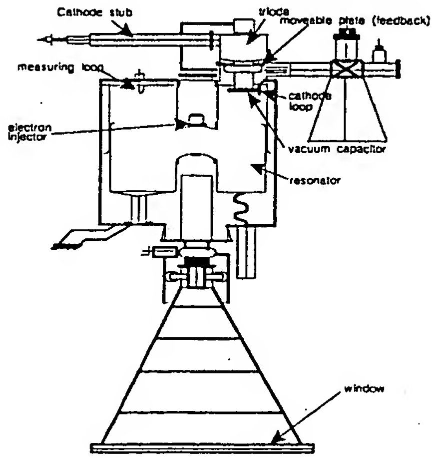

Fig. 2 NOVOSIBIRSK SELF-EXCITED LINAC

The Efremov Institute has a well established reputation for the design and manufacture of travelling wave linacs. They are now manufacturing on-axis coupled standing wave linacs for medical and industrial applications (Vakhrushin et al., 1988). These structures were first developed at Chalk River Nuclear Laboratories and form the basis of Atomic Energy of Canada Ltd.'s industrial linac program. A new invention for providing variable energy in a standing wave linac is under development in Leningrad. The introduction of four symmetric tuners into one of the accelerating cavities allows the cavity to be tuned so that a TM_{011}-like mode can be excited at the same frequency as the fundamental TM_{010} mode of neighbouring cavities. This causes a phase reversal in the middle of the cavity, which retards the previously accelerated beam. Reports on the status of these developments are awaited with interest.

MARKET DEVELOPMENT

Radiation Facilities

At the end of this decade, there will be 142 electron irradiators operating in Asia with a total beam power greater than 5.7 MW (Mizusawa, 1989). Cross-linking of wire insulation is the main industrial application while 30% of the machines are used for research and development. Nissin High Voltage is the lead supplier. All of these machines are of the dc-type and the technology is now mature. The largest of the machines in Japan was built by RDI (5 MeV, 40 mA) for the new facility being constructed by Sumitomo Heavy Industries in Tsukuba, Japan. RDI have 150 Dynamitrons in service, of which 26 are rated from 2.5 to 3.0 MV and 16 from 4.0 to 4.5 MV.

Table 3 provides a list of known linac installations with energies above 5 MeV that are used either in industrial applications or operated commercially. Some of these machines use the latest in industrial linac technology and are worthy of special mention.

FACILITY	ENERGY RANGE (MeV)	AVERAGE POWER (kW)	BEND	SCAN WIDTH (cm)	HORN (m)
IRT, San Diego	6 - 18	2 x 7	90°	38	2.4
Riso, Denmark	6 - 14	10	90°	60	2.1
Raychem, Demark	10	10	90°	60	3.0
Warsaw, Poland	13	9	270°	-	1.5
Caric, France	5 - 10	20	0°	60	1.4
LUE 28-5U, USSR	8	2 X 5	-	50	-
HPR, Budapest	4 - 11	7	-	-	-
WNRE, Canada	9 - 11	1	270	60	1.5
SCANCARIC, Sweden	10	25	0	80	1.4
ALDERMASTON, England	10 - 14	24*	0	-	-
HARWELL, England	8 - 12	25	90°	-	-

* Theoretical rating, for safety reasons operating levels restricted

TABLE 3: High Energy Electron Irradiation Facilities

The Aldermaston linac designed by Haimson Research Corporation has been in operation for the past decade at the Aldermaston Weapons Research Establishment in England and its performance has recently been declassified. The beam emerges through a titanium window providing dose rates up to 100 MGy/s for use in studying the effects of transient radiation on semiconductor devices. This is probably the highest instantaneous dose rate available commercially.

Of special interest is the new Scan Caric facility in Sweden. This new facility uses a 10 MeV linac manufactured by CGR MeV, France and the accelerator has achieved a power level of 20 kW during commissioning. A diagrammatic representation of the facility is shown in Figure 3. Medical sterilization and the processing of new materials are prime commercial targets.

The new I-10/1 facility at the Whiteshell Nuclear Research Establishment (WNRE) is now in full operation (Barnard and Stanley, 1988) as shown in Figure 4. It is a fully automatic machine requiring negligible accelerator knowledge by the operators. Energy, power and conveyor speed are under closed loop control supervised by an industrial programmable controller. This is probably the only short pulsed linac in existance where these parameters are continuously monitored and controlled in a closed loop. Applied Radiation research dominates facility use. Work programs are underway in food, sterilization, biomass, paper making and the development of new materials for the aircraft and aerospace industries (Saunders and Singh, 1989).

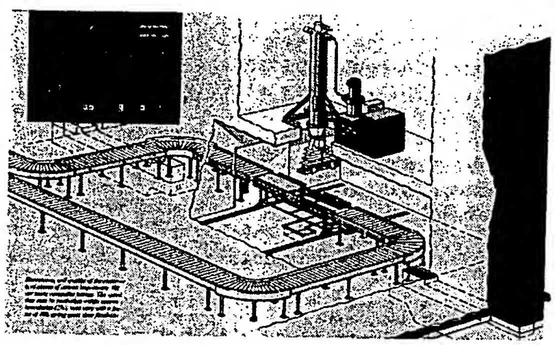

Fig. 3 The Scancaric Facility, Sweden

Fig. 4 The Whiteshell Facility, Canada

New Products

New accelerator designs are under development in North America and elsewhere. Industrial versions of the linear induction accelerator widely touted at the San Diego conference four years ago, are evolving slowly. One such design has been run at 1.6 MeV and 20 kW (Bayless and Burkhart, 1989). It is claimed that magnetic pulse, compressor-type short pulse generators could give high efficiency (60%).

The 50 kW prototype of the AECL series of linacs called IMPELA is undergoing its commissioning tests at CRNL. The fully automatic rf system is working under computer control and the single large klystron has powered the rf structure to the design energy of 10 MeV. A feature of this design is closed loop control of the accelerating field during the pulse. Fig. 5 demonstrates how the drive signal to the klystron must be increased to ensure a constant energy. This type of control is only possible in a long pulse or CW linac. Performance tests have shown energy stability during the pulse of better than 1%. Initial beam tests are consistent with design expectations and full power is planned for June 1989.

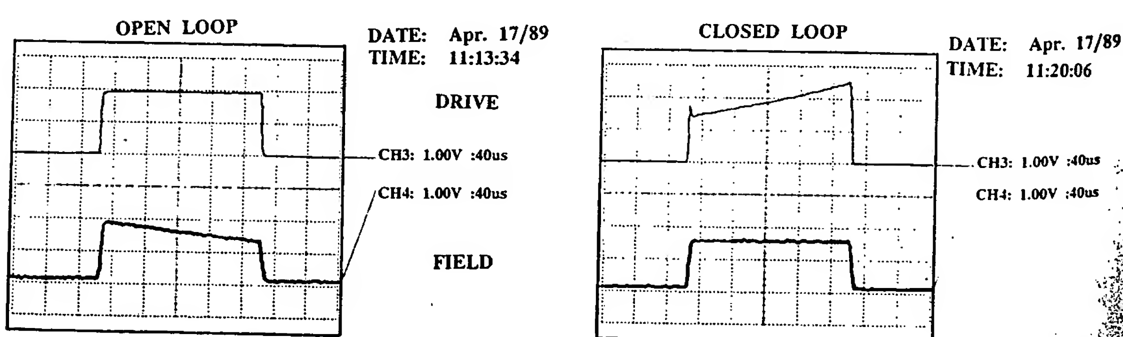

Fig. 5 Closed loop control of the rf field in IMPELA

Summary

A bright future is seen for electron accelerators in radiation processing. New applications in nuclear waste incineration and as synchrotron light sources for x-ray lithography are being vigorously pursued. Exciting advances in solid state chemistry are coupled with new linac designs from the USSR giving encouragement to wider industrial use of radiation. New service centres have come into being since the last conference and new industrial linacs are emerging from established design teams in France and in North America.

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